## 2.1 Introduction To Damage Concepts and Behavior

Past experience with tests of structures under simulated flight loading has indicated that the time to initiation of cracks from most structural details such as sharp corners or holes is relatively short and that the majority of the life (i.e., 95%) is spent growing the resultant cracks to failure. Likewise, analyses of in-service fractures, cracking instances, etc. have indicated that a major source of cracks is the occurrence of initial manufacturing defects such as sharp corners, tool marks and the like. Thus, it is now common practice to consider the damage accumulation process as entirely crack growth, with zero time to initiate the crack. Although this assumption may seem unduly severe, recent studies have shown the approach feasible, of minimal detriment to weight, cost, etc., but most important, the consideration of initial damage in the form of cracks or equivalent damage is absolutely necessary to ensure structural safety.

This subsection will detail the fundamentals of life prediction based on crack growth. The crack length will be the measure of damage and the crack growth rate will define the rate of damage accumulation.

### 2.1.1 Damage Growth Concepts

Figure 2.1.1 presents a schematic of typical growth behavior for a crack being observed in a structural element as it moves from an initial damage size to a damage size that causes structural failure (loss of structural safety). Note that the x-axis measures either the elapsed time ($t$) during which loading is applied or the number of loading events ($N$) applied, and the y-axis measures the corresponding length of crack observed in the structure. Typically, the elapsed time is given in operational flight hours and the number of loading events is counted (grossly) by the number of the aircraft's flights.
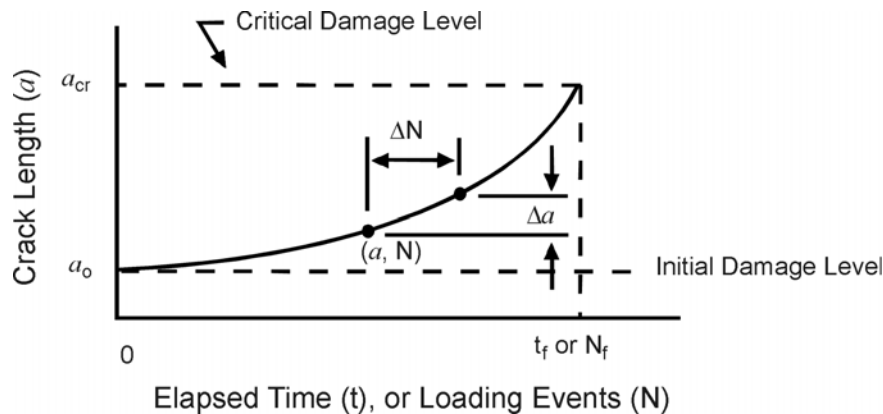


**Figure 2.1.1.** Schematic of Observed Crack Growth Behavior for a Typical Structural Cracking Problem

The crack grows in response to the cyclic loading applied to the structure. Any crack will grow a given increment ($\Delta a$) in a given number of loading events ($\Delta N$), the rate being measured by $\Delta a/\Delta N$. When the crack length reaches a critical value ($a_{cr}$), the growth becomes unstable, thereby inducing failure.

When the crack ($a$) reaches the critical length, the measure of loading ($t$ or $N$) reaches the structural life limit ($t_f$ or $N_f$). The structural life limit is a measure of the maximum allowable service time (or number of accumulated service events) associated with driving the crack from its initial length ($a_o$) to the critical length ($a_{cr}$). It is the objective of the Damage Tolerant Requirements to ensure that cracks do not reach levels that could impair the safety of the aircraft during the expected lifetime ($t_s$ or $N_s$) of the aircraft, i.e., $t_f$ ($N_f$) must be greater than $t_s$ ($N_s$).

As can be noted from Figure 2.1.1, when the crack is small, it grows very slowly. As the crack gets longer, the rate of growth increases until the crack reaches the critical size $a_{cr}$, whereupon fracture of the structural element ensues. While the subcritical crack growth process occurring for $a \leq a_{cr}$ may take twenty to thirty years of service, the fracture process is almost instantaneous. Studies of the failure process indicate a very close relationship between the length of crack at failure and the load or stress that induces the onset of rapid fracture.

Typically, this relationship between crack length and failure strength level is as shown in Figure 2.1.2. The cracked element strength is referred to as the residual strength ($\sigma_{res}$) since this represents the remaining strength of a damaged structure. By considering the basic elements of Figures 2.1.1 and 2.1.2 collectively, a residual strength diagram can be developed as a function of elapsed time (or loading events).
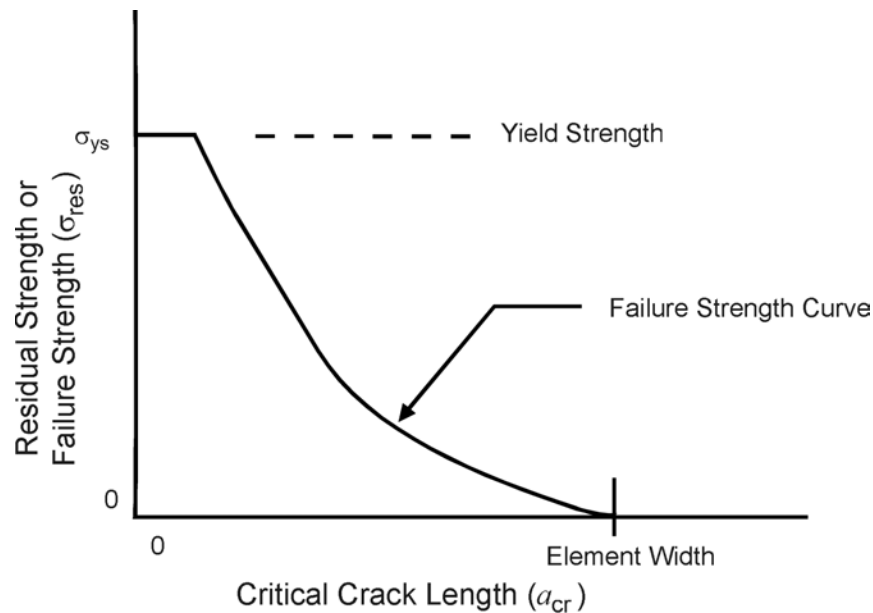


**Figure 2.1.2.** Schematic of Relationship Between Failure Strength and Crack Length for a Typical Single Element Type Structure

A residual strength diagram is presented in Figure 2.1.3; this diagram shows that while the structure is young ($t \ll t_f$) the residual strength capacity is basically unimpaired because the crack is both small and doesn't grow much with time. As the structure starts to age, the residual strength capacity is shown to decrease and just prior to failure, the rate of decrease in residual strength capacity is accelerating because now the crack is rapidly becoming very large. When

the residual strength capacity equals the level of the maximum stress in the operational history, failure occurs.
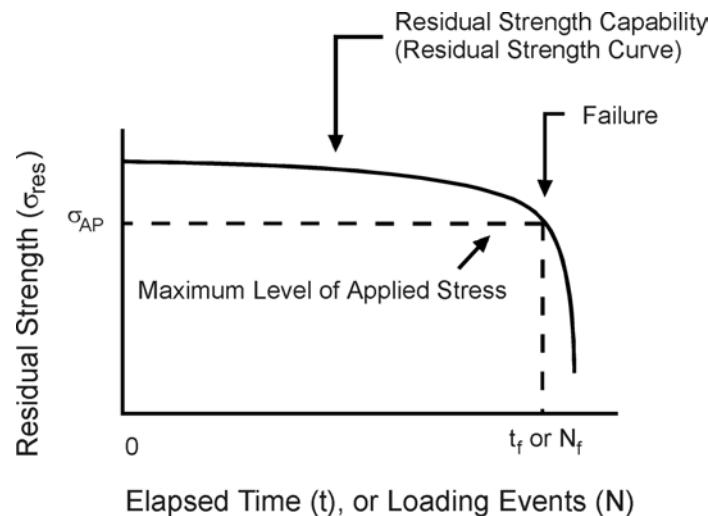


**Figure 2.1.3.** Residual Strength Diagram Relationship Between Residual Strength Capacity and Elapsed Time

As implied by the residual strength diagram, a ten to twenty percent change in the maximum applied stress in the operational history would not normally affect the allowable structural life significantly, assuming that the subcritical crack growth process (Figure 2.1.1) was unaffected. Normally, when the loads in the operational history change, the subcritical crack growth process changes its pattern of growth and this in turn affects the residual strength diagram and the allowable structural life.

## 2.1.2    Damage Growth Behavior/Effects

As discussed above, the crack length $a_o$ will grow to $a_{cr}$ in some life $t_f$, and as the crack grows the residual strength capability decreases. Experiments have shown that several parameters affect the crack growth life; the most important of these being the initial crack size, $a_o$, the load history, the material properties, and the structural properties. The isolated effect of each parameter on the crack growth behavior and the residual strength curves will be discussed in turn using the baseline conditions identified in Figure 2.1.4. The interrelation of these parameters will be developed in the discussion of life prediction methodology (Section 2.4).
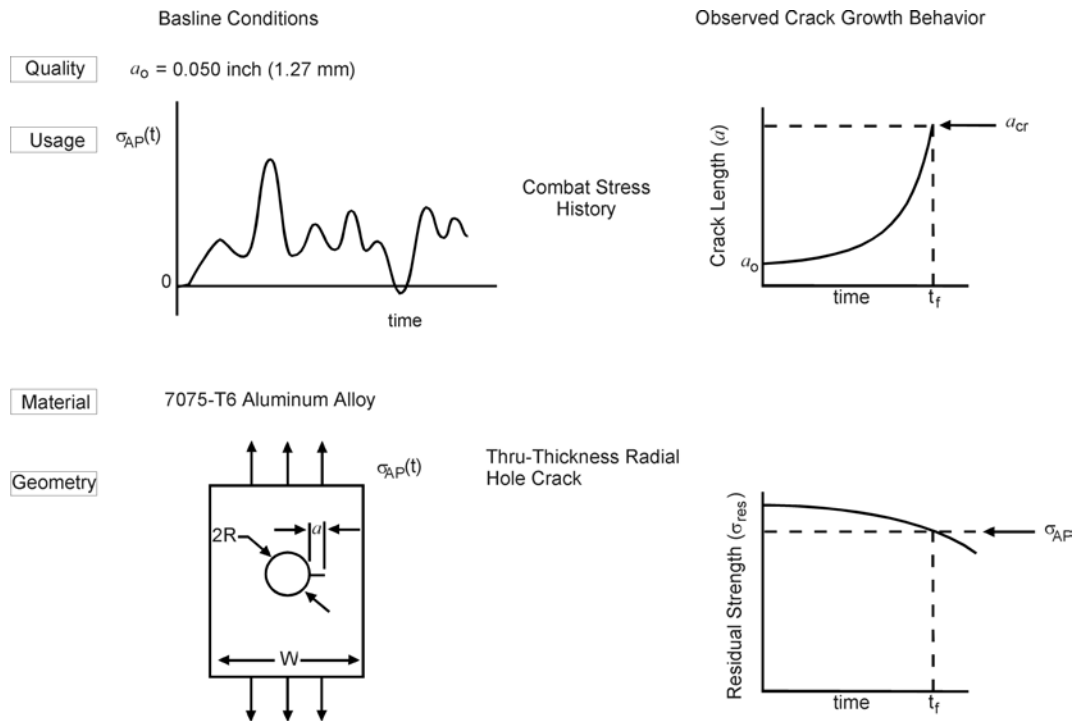
**Figure 2.1.4.** Description of Baseline Conditions for Observed Crack Growth Behavior

Initial Crack Size – A Measure of Quality

The effect of initial crack size is significant.  Given a configuration and loading, the smaller the initial crack size, the longer the life and the higher the residual strength capacity at any time. These observations are displayed in Figure 2.1.5a and b, respectively.  Note that the shape of the crack growth curve (for a given configuration and loading) remains essentially constant for any given crack growth increment.

Thus, given the crack growth curve for the smaller initial crack, it is possible to construct the crack growth curve for the baseline condition.  This can be accomplished by shifting the crack growth curve with a smaller initial crack horizontally to the left until the curve intersects the vertical axis at the baseline initial crack size.  Also, note that the residual strength curve for the baseline condition can be constructed from the curve obtained for the smaller initial crack size.
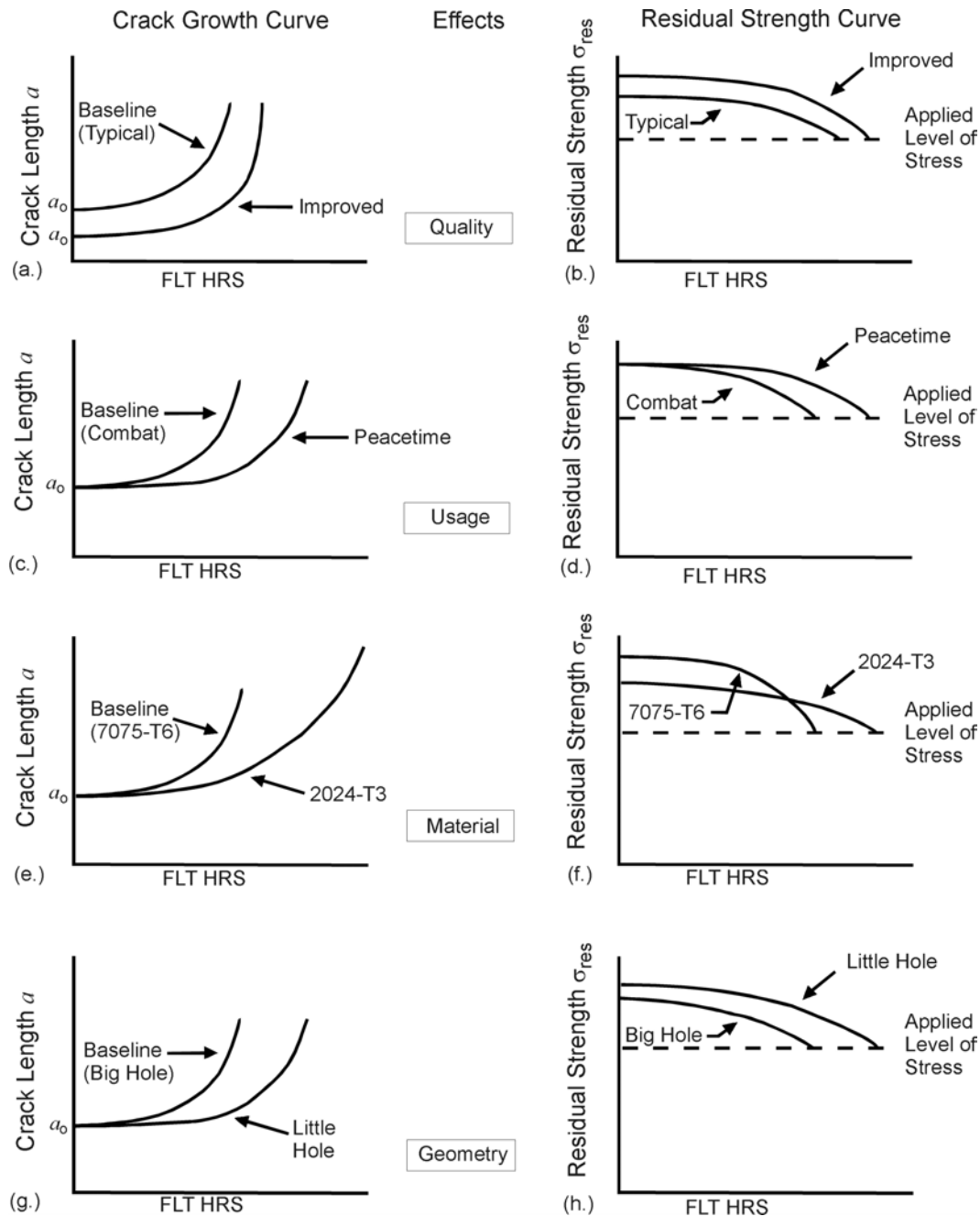
**Figure 2.1.5.** Schematic Summary of the Effects of Quality, Usage, Material, and Geometry on Both the Crack Growth and Residual Strength Curves

Stress History - A Measure of Usage and Location

As an aircraft flies different missions and different maneuvers, it experiences different loadings. The magnitude and sequence of aircraft loadings are noted to have a significant effect on the rate at which cracks grow. The stress history describes the magnitude and sequence of stresses at one location that results from the sequence of missions or maneuvers that an aircraft flies. Figure 2.1.5c and d illustrate the effect that stress history (usage) can have on the crack growth behavior

and residual strength capacity, respectively.  While it was not shown, a change in stress history will normally also change the applied stress level at which fracture occurs.

The stress history experienced at each location on the aircraft will also differ due to changes in bending moment, twisting moment, shear loading, etc., given a particular crack configuration (e.g., a crack growing from a fastener hole on a wing).  The loading spectra for a lower surface location is typically more severe than a corresponding upper surface location; and, therefore, the life for the lower surface will be significantly shorter than that of the upper surface all other conditions being equal.

Material Properties - A measure of Material Resistant to Cracking

Experimentally, it has been shown that for the same loading condition (i.e., the same number and amplitude of stress cycles) cracks will grow faster in certain alloys than in others.  The crack growth rate $(\Delta a/\Delta N)$ can be derived experimentally for each material.  Given the same load and geometric conditions, the alloy having the slower growth rate characteristics (i.e. 2024-T3) will have a longer life $(t_f)$ as shown in Figure 2.1.5e.  This material also has some inherent resistance to fracture.  The higher this inherent resistance, the higher the residual strength capacity for any crack length.  This effect is described in Figure 2.1.5f.

If the cracks are so small that the fracture process is controlled by gross yielding, then the residual strength curve is controlled by a net section failure criterion rather than a fracture criterion.  In this case, the material with the highest yield strength would have the highest residual strength in the region of the curve controlled by the behavior of the small cracks.

Structural Properties - A Measure of Geometry

The most complex of the parameters affecting crack growth behavior are the structural properties.  The structural properties involve such things as crack configuration, load transfer through fasteners, fastener hole size, part thickness, etc.  A substantial amount of experimental work has been performed to characterize the geometrical effects on life.  The effect of a change of hole radius on the crack growth behavior and on the residual strength capacity is shown in Figure 2.1.5g and h.  The structure with the smaller hole, and thus the smaller stress concentration is noted to have the longer life and higher residual strength.

Summary of Effects

As discussed above, there are four major parameters that affect the crack growth life and residual strength capacity of structures.  These parameters are in the realm of quality (initial crack size), usage (loading history), material (material properties), and geometry (structural properties).  Figure 2.1.6 has been prepared to summarize the parameters' effect on life and to illustrate various presentation schemes that might be employed to compare effects.
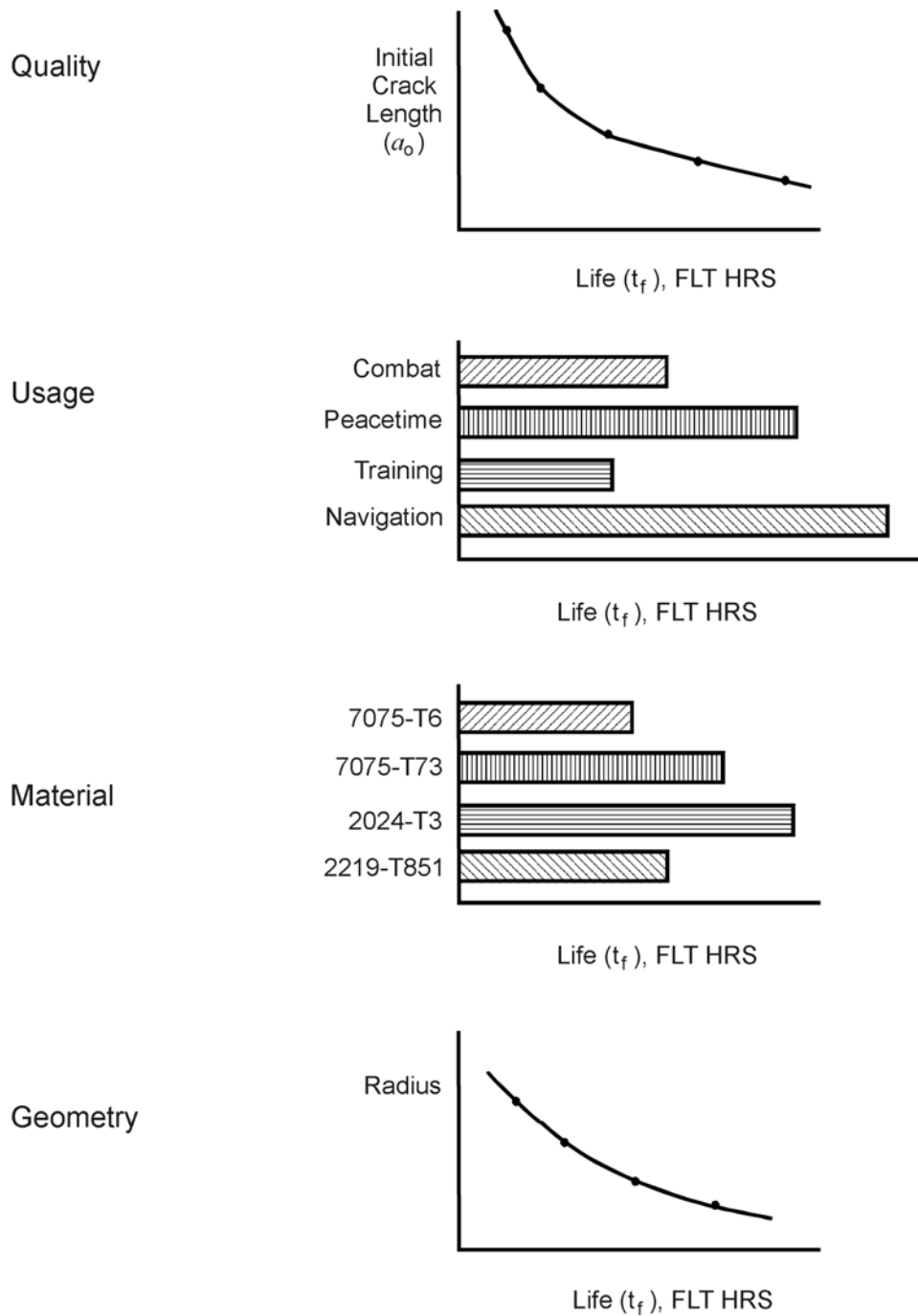
**Figure 2.1.6**. Summary of Schemes Which Illustrate the Sensitivity of Life to Various Structural Parameters